

**A REVIEW OF THE STATE OF THE ART
IN PAPER DRYING**

Project 3394

**Report One
A Progress Report
to
MEMBERS OF THE INSTITUTE OF PAPER CHEMISTRY
February 29, 1980**

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

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A REVIEW OF THE STATE OF THE ART
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SUMMARY

A review of the economics of papermaking shows the importance of material costs, productivity and capital, and lesser importance of energy. However, yearly operating costs are dominated by dryer steam use. The most important actions to reduce operating costs (in order of priority) are:

1. Increase dryer efficiency;
2. Improve wet pressing;
3. Improve web moisture uniformity.

A review of the literature shows that the most thoroughly researched area is convection drying. It is recommended that future IPC dryer research emphasize two areas:

1. The improvement of the operation of existing drum dryer sections;
2. The study of the fundamentals of paper web transport phenomena
in order to develop new methods of drying.

INTRODUCTION

In order for the Institute to establish a firm base for future research, a thorough review of the state of the art in paper drying was undertaken. Three methods were used to collect information on drying: a review of the literature, mill visits, and interviews with drying experts. The data from these sources were combined to identify the strengths and weaknesses in the art of paper drying. This report summarizes the factors that influence drying technology and then evaluates the state of the art.

BACKGROUND

Drying technology is influenced by economic factors — both mill economics and paper machine economics. These factors have a direct bearing on dryer research, design, and operation.

PAPER MILL ECONOMICS

Five economic factors that influence the rate of return on investment in a paper mill are shown in Table I. The most important factor is materials cost which causes the largest change in return on investment and is assigned a relative value of 100. The next is volume or productivity which has a value between 85 and 90. Capital has a value between 60 and 65, and labor and utilities are both between a value of 10 and 15.

TABLE I
SENSITIVITY ANALYSIS OF PAPER PRODUCTION
ECONOMIC FACTORS^{a,b}

Economic Factor	Influence of Rate of Return
1. Material costs	100
2. Volume (productivity)	+ (85-90)
3. Capital	60-65
4. Labor	10-15
5. Utilities	10-15

^aReference (1).

^bThe values are normalized slopes of the return on investment curves given by S. Bruce Smart, Jr. (1).

Thus, the most important actions to improve the rate of return in a paper mill are to reduce material costs and increase productivity. The material costs can be reduced by substituting a cheaper furnish and by reducing material loss and recycle. The material loss/recycle can be reduced by improving the uniformity of paper quality. In terms of drying, this translates into a need for more uniform moisture profiles.

Productivity can be increased by increasing the production rate and reducing the downtime. In drying, this corresponds to the need to increase the evaporation rate on dryer-limited paper machines and to increase the machine uptime by reducing web flutter and breaks.

The second most important action is to decrease capital costs. This translates into the need to reduce the size and capital cost of new dryers.

The efficient use of energy in papermaking has been downplayed in the past. However, skyrocketing energy prices are forcing a new look at this factor. Thus, the overall paper mill objectives (in order of priority) are:

1. Reduce material costs
2. Increase productivity
3. Reduce capital costs
4. Reduce energy costs

PAPER MACHINE ECONOMICS

In contrast to paper mill economics, paper machine operating costs are dominated by drying energy costs. This is a result of the fact that the other economic factors are fixed. The required furnish is dictated by the paper grade being made, the paper machine is already run at its maximum production rate, and

the capital cost is fixed once the machine is purchased. Thus, the main variable left to affect operating cost is energy.

An analysis of paper machine economics (2) shows the importance of the dryer section. As shown in Fig. 1, less than 1% of the water is removed at the presses and less than 0.5% is removed in the dryers. However, the cost of removing that last bit of moisture in the dryer dominates paper machine water removal costs as shown in Fig. 2. Also, drying costs have arisen dramatically since 1973. Paper machine operating costs (not including furnish and labor) have followed the drying cost trend since steam costs are about 75% of operating costs (3). Thus, reducing dryer energy costs has been an important goal.

There are basically three things that can be done to reduce the dryer operating (energy) costs: (a) increase the dryer energy efficiency, (b) remove more water before entering the dryer, or (c) increase the amount of water that is left in the paper after drying.

The reduction in paper machine operating costs with increasing dryer efficiency is shown in Fig. 3. This reduction is much more pronounced now than it was in 1973. Increasing the dryer efficiency from 65% to 80% would save over \$785,000/year in a 1000 TPD mill.

The reduction in paper machine operating costs with decreasing press moisture is shown in Fig. 4. Again, the effect is much more pronounced now than in 1973. Reducing the press moisture from 60% to 55% would save \$700,000/year in a 1000 TPD mill. Thus, decreasing the press moisture (i.e., improving wet pressing) has been an important research and development goal.

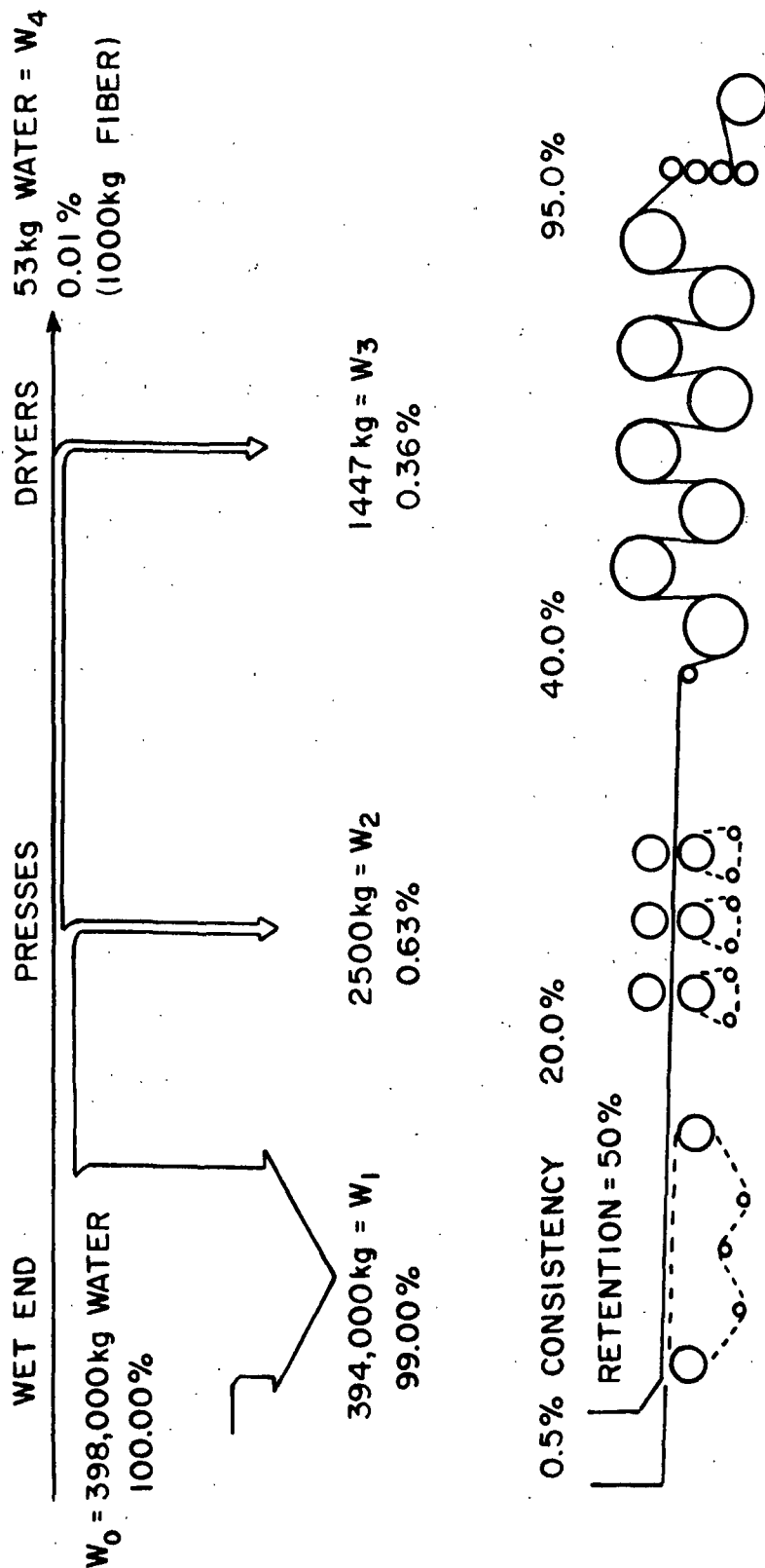


Figure 1. Paper Machine Water Removal

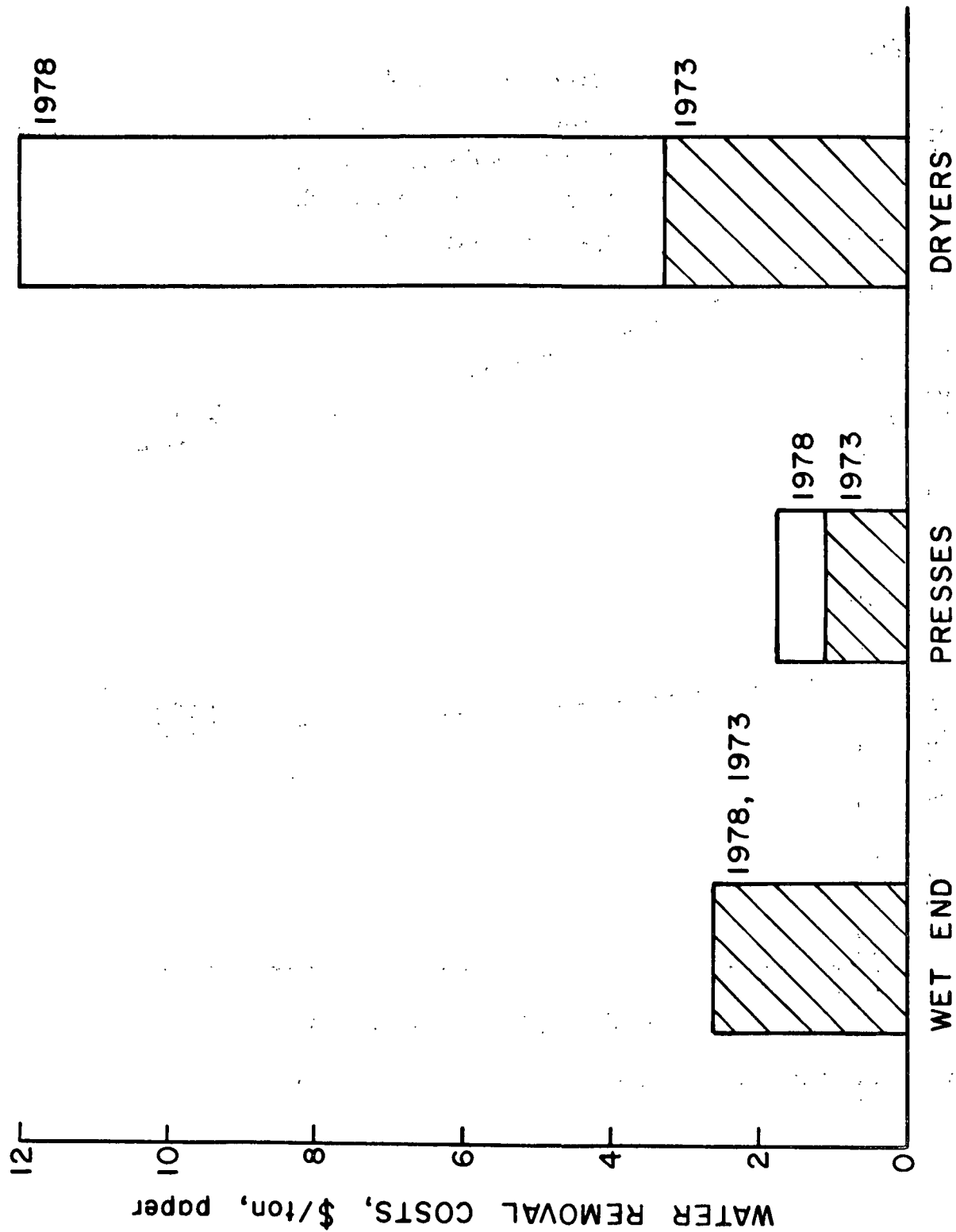


Figure 2. Water Removal Costs for the Wet End, Presses and Dryers

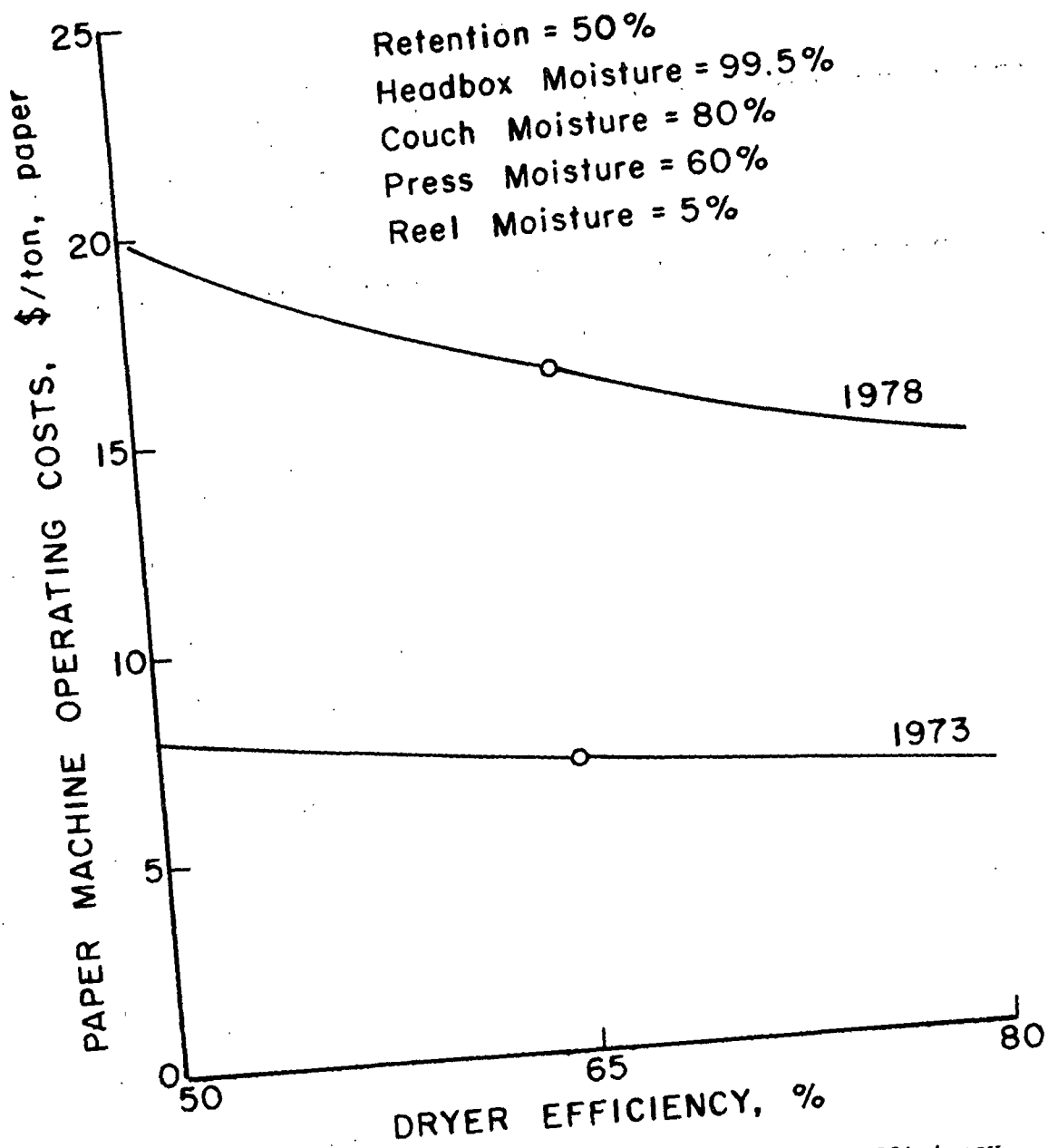


Figure 3. Paper Machine Operating Costs Versus Dryer Efficiency

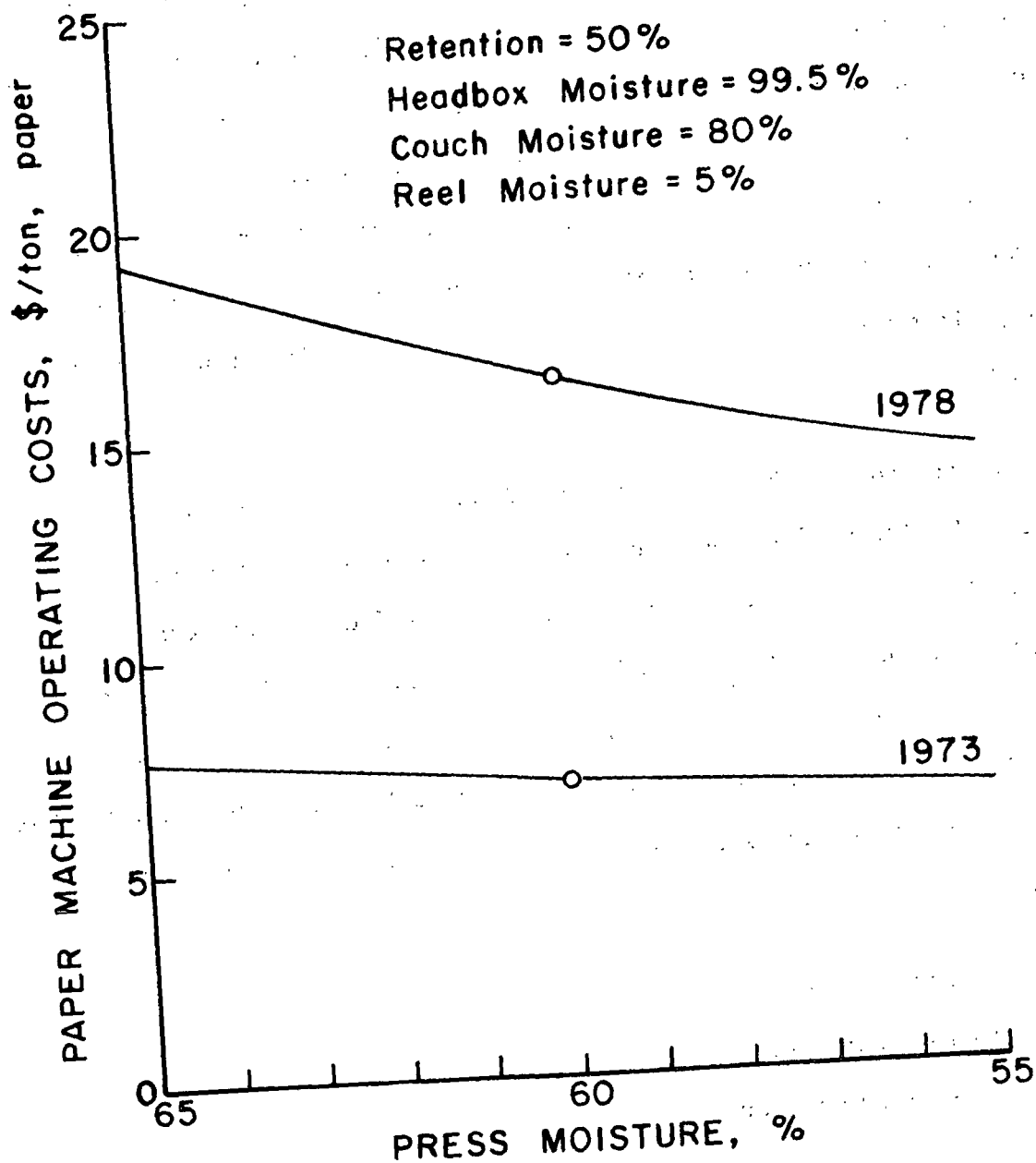


Figure 4. Paper Machine Operating Costs Versus Press Moisture

Finally, the reduction of paper machine operating costs with increasing reel moisture is shown in Fig. 5. Increasing the reel moisture from 5% to 10% would save over \$400,000/year in a 1000 TPD mill. The reel moisture targets can be raised by improving the cross direction (CD) moisture uniformity. Many paper-makers now overdry the sheet to improve the moisture profile and to eliminate wet streaks. Raising moisture targets would have its greatest impact in increasing productivity since most of the dryer section is used to reduce the moisture content from 10% to 5%.

A comparison of the relative reductions in paper machine operating costs by increasing the dryer efficiency, decreasing press moisture, and increasing reel moisture is shown in Fig. 6. Increasing dryer efficiency reduces costs slightly more than decreasing press moisture. However, costs increase much more rapidly with decreasing dryer efficiency than with increasing press moisture. Increasing reel moisture is shown to have a secondary effect on reducing operating costs. Thus, the actions to reduce paper machine energy costs (in order of priority) are:

1. Increase dryer efficiency
2. Improve wet pressing
3. Improve CD moisture uniformity.

The results of this sensitivity analysis apply to any type of dryer section.

In order that one could determine the importance of different types of dryers an estimate of the distribution of dryers in the paper industry was made. This is shown in Table II. First, the percent water removed in each drying application was estimated based on the assumption that the water removed is proportional

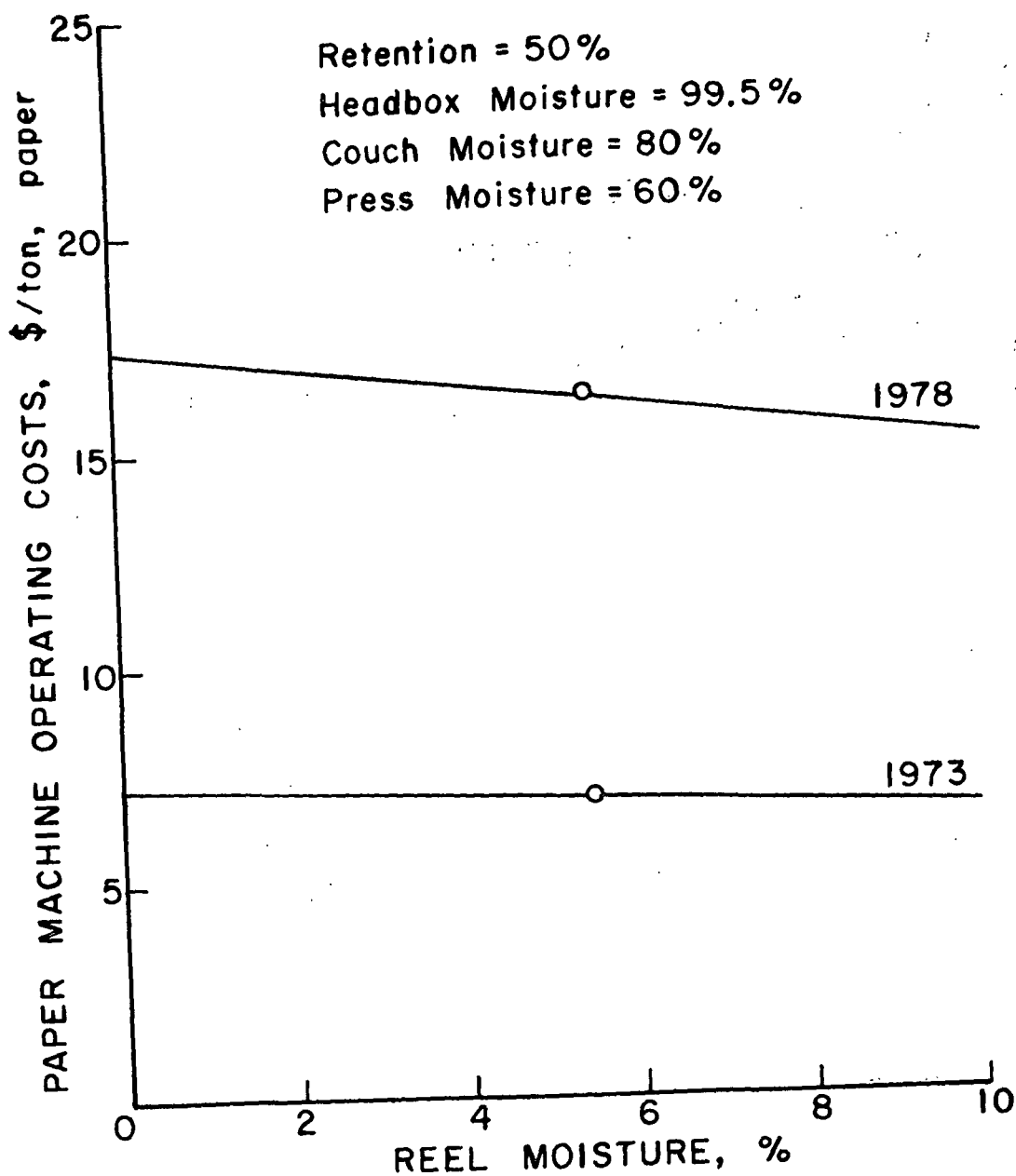


Figure 5. Paper Machine Operating Costs Versus Reel Moisture

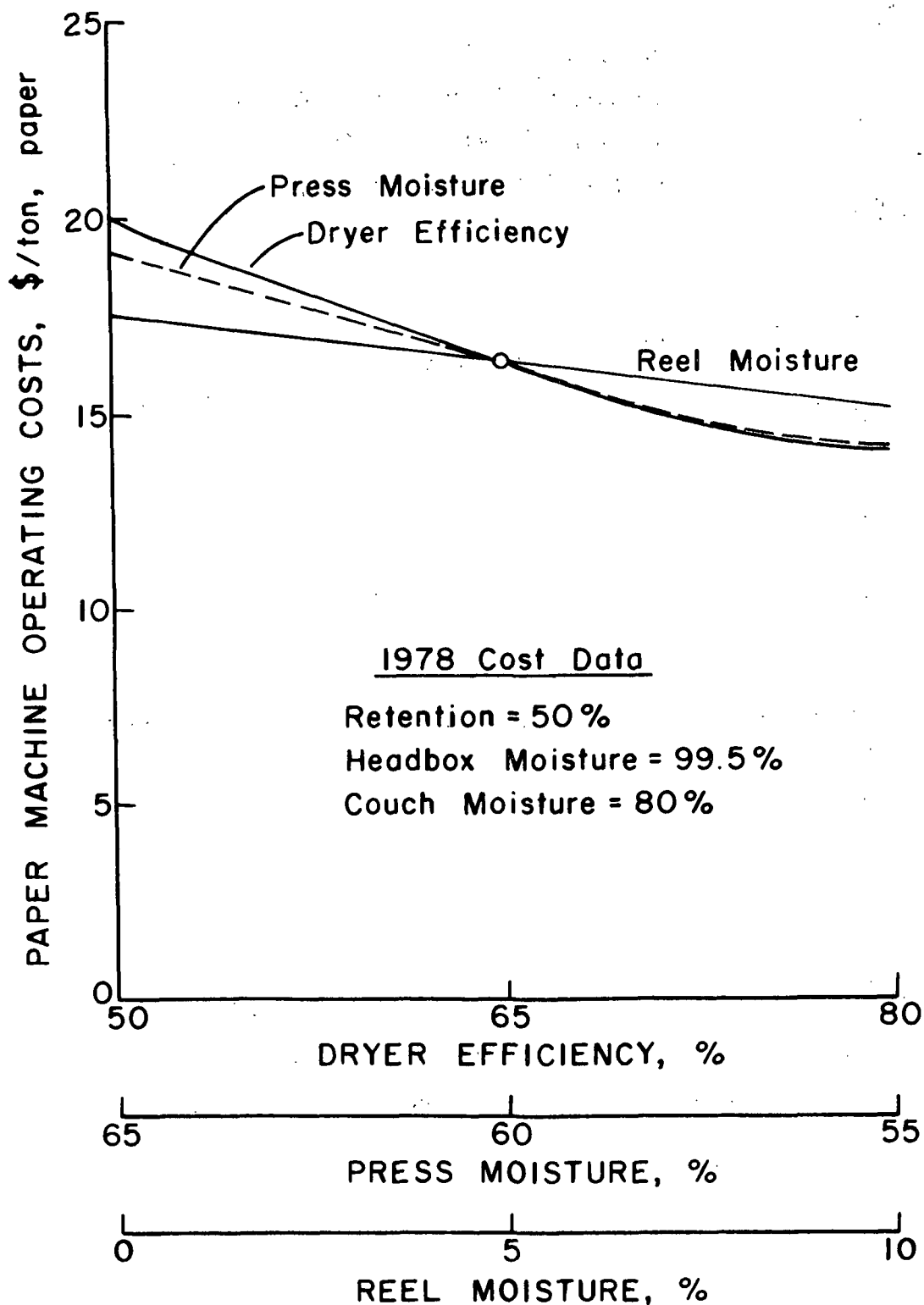


Figure 6. Paper Machine Operating Costs Versus Dryer Efficiency, Press Moisture, and Reel Moisture

TABLE II

U.S. PAPER INDUSTRY DRYER DISTRIBUTION

	Paper Industry Drying Application ^a					Totals, %
	Pulp	Tissue	Paper	Board	Coating	
	Water Removed, %					
	7	6	34	51	2	100
	Dryer Distribution, %					
Drum section dryer		15	95	95	35	82.35
Impingement dryer	70		2	2	50	7.60
Yankee dryer		70				4.20
Infrared dryer			3	3	15	2.85
Through dryer		15				0.90
Flash dryer	15					1.05
Vacuum dryer	15					1.05
Dielectric dryer						
Microwave dryer						
Totals	100	100	100	100	100	100.00

^aThis includes both on- and off-machine coating operations.

to the product produced. Thus, about 7% of the industry water removal is in pulp drying, 6% in tissue drying, 34% in paper drying, 51% in paperboard drying, and 2% in coatings drying. Next, the distribution of the types of dryers for each application was estimated. For example, in pulp drying it is estimated that 70% of the pulp is dried in impingement (floater) dryers, 15% in flash dryers, and 15% in vacuum dryers. After the dryer distribution for each application was determined the total percentage water removed on each of the types of dryers was determined by multiplying

the percent of the dryer distribution by the fraction of water removed in the corresponding application. This shows that 80-85% of the industry's drying is done on conventional drum dryers. Approximately 5-10% of the drying is done on impingement dryers. About 4-5% of the drying is done on Yankee dryers. Less than 3% of the drying is done on infrared dryers. Through, flash and vacuum dryers each account for about 1% of the drying. Finally, almost no drying is done on dielectric and microwave dryers. Thus we see that the conventional drum dryer is dominant in the industry. The impingement dryer is the next most important. It is used mainly for drying pulp and coatings. Yankee dryers follow in importance and dominate tissue drying. Thus, research on improving existing dryers should focus on conventional drum section dryers.

REVIEW OF DRYING

There is relatively little written on a unified treatment of paper drying. The book by Keey (4) covers all aspects of industrial drying but has little specifically on the drying of paper. The chapter by Coveney and Robb (5) on the dryer section is mostly descriptive of equipment and has a little analytical treatment of dryers. The book edited by Gavelin (6) is the best available on the drying of paper, but suffers from the fact that it is a series of articles and not a unified text by one author. Other similar, but less complete, article series were edited by Cirrito (7-17) and Blundell (18-24).

There have been several reviews of drying that are helpful. The review by Han (25) discusses work on modeling the transport phenomena occurring in the dryer. The reviews by Burgess (26,27) compare the principles and economics of several drying methods: conventional drum section, high velocity hoods, dielectric and microwave, radiant, fluidized beds, and through dryers. Most of the other papers on drying describe a particular dryer type.

DRUM DRYERS

Several workers have analyzed conventional drum dryers. However, all the past web modeling work has been done for evaporation at one atmosphere in air. Nissan (28-32) was the first person to model a conventional drum dryer section. The drying process was modeled by a dynamic thermal diffusion equation with time-varying boundary conditions. The work by Snow (33) extended this model by including the transient moisture flow in the web. He included the capillary flow of liquid and the diffusion of vapor. The model by Holm (34) incorporated earlier work by Han (35-36). This model included moisture flow by capillary, diffusion, and pressure

gradients. Thus, these models emphasized the temperature and moisture profiles in the web.

Other researchers have not included as much detail about the transport phenomena in the web, but have emphasized other subsystems. The best example of this is in the model developed by Knight and Kirk (37) based on Knight's thesis (38). Their model includes the drum steam and condensate dynamics as well as pocket ventilation. Kirk (39) has used the model to study the effect of different pocket ventilation flow patterns on the CD moisture profile. Depoy (40) and Meisel (41) used an analog computer to simulate a dryer section using a model similar to that developed by Nissan. Other examples of models based on Nissan's work are those by Strong and Powell (42) and Lehtikoski (43). Rhodius and Gottsching used a similar model (44) but did extensive experimental work (45-47) determining the parameters that affect drying rate. Their experimental technique is similar to that used by Lee and Hinds (48) to determine the effect of wet pressing, refining, and surface texture on drying. Thus, a good start has been made on understanding conventional drum dryers. However, a thorough study should be undertaken to determine the transport coefficients to predict drying rates and energy efficiency. Also, methods to improve CD moisture profiles are needed.

YANKEE DRYERS

The main components in a Yankee dryer are the steam-heated drum and the high velocity hood. Researchers have worked on characterizing the heat transfer from both of these sources. Zabel (49) used an analog computer to simulate the heat transfer in a Yankee dryer shell. His results agreed with earlier experimental work by Brauns and Jansson (50) showing that most of the temperature changes occur under the press roll and in a thin layer of the shell next to the web. Their

experimental technique was extended by Sundberg, et al. (51) for use in mill operation. Schiel and Zurn (52) used calculations of the thermal resistances of the paper, shell, and condensate to determine the capacity of Yankee drums with plain shell, plain shell with spoiler bars, and grooved shell.

Most of the work on Yankee dryers has been concentrated on the high-velocity hood. Spraker, et al. (53) used a simple lumped-parameter model to relate heat and mass fluxes to the temperature and humidity differences. Rounds and Wedel (54) calculated the theoretical drying rate and specific energy consumption of a Yankee hood as a function of the supply air humidity and temperature, and the impingement velocity and open area.

Several investigators have studied the heat transfer in air-impingement drying. Daane and Han (55) correlated the turbulent heat transfer coefficient to the Reynolds number, Prandtl number, and geometrical factors for single and multiple round jets and slots. Larsson (56) compared several impingement heat transfer correlations and high velocity hood designs. Han and Seely (57) analyzed the heat transfer from single and multiple round jets by similarity with momentum transfer, using the Blasius Law for turbulent flow in a pipe. Mujumdar and Douglas (58) surveyed the literature on the heat transfer characteristics of two dimensional slot jets, single jets, and arrays of round jets impinging on flat and curved surfaces. Other correlations for impingement heat transfer are given by Batsis and Schukow (59) and Christ and Weinmann (60). A summary of the state of the art in impingement heat and mass transfer is given by Martin (61). Other authors have emphasized the practical aspects of Yankee hood applications. Andersson (62) gives an overview of the design and use of high velocity hoods. Villalobos (63) has discussed blow-through and draw-through fan arrangements, the importance of humidity levels, and the relative merits and problems of heat recovery. Methods are also

available (64) for evaluating high-velocity dryers. Finally, Villalobos (65) has discussed the use of a gas turbine with a Yankee dryer to improve the utilization of available work.

Thus, much work has been done on Yankee dryers. The analysis of Yankee dryers is more advanced than that of conventional drum dryers.

CONVECTION AND THROUGH DRYERS

Two of the most active areas of drying research in recent years have been convective and through drying. Holik (66) discussed the main considerations in through drying and developed a simple drying model. In a later paper, Holik (67) presented a review of convection drying.

Villalobos has written three papers on through drying. In the first (68), he discussed the main factors in the design and operation of through dryers. The second (69) pointed out the benefits of operating through dryers at low temperatures. The third (70) described the through-drying processes used in the manufacture of tissue and toweling.

Several models of convective and through drying have been developed. Crotogino (71) reviewed the factors governing the drying rates attainable with impingement and through drying in his survey of convective drying. Crotogino and Galatone (72) modeled a Papridryer by adding the impingement- and through-drying rates. Gardiner has written three papers discussing his through-dryer model. In the first (73), he outlined the model and described the sensitivity of design and operating parameters on dryer capacity, drying rates and operating costs. The second (74) showed the effects of hood temperature and humidity on energy efficiency. The third (75) developed the general relations between energy consumption and drying

capacity for convective dryers in general. Wedel and Chance (76) developed a distributed-parameter model of through drying and used it to predict the drying rate and energy consumption. The operation of convection and through dryers is fairly well understood. The ongoing research in this area seems to be adequate.

VENTILATION

The work on ventilation can be divided into hood air systems and pocket ventilation. Most of the articles on hood air systems have been qualitative instead of quantitative. Marshall (77) gave an overview of dryer hood selection and use. Walker (78) described some of the benefits of a well designed air handling system. Reed (79) and Walker (80) outlined some energy conservation measures in air handling systems. Of the many articles on pocket ventilation, most are descriptive. Kottick (81) gave a short overview of pocket ventilation. Soininen (82) analyzed the air flow patterns caused by permeable dryer fabrics. Soininen and Nurminen (83) described how a pocket ventilation system can level the web moisture profile. Kottick (84) discussed the use of pocket ventilation on a high-speed newsprint machine. Several authors (85,86,87) show examples of how pocket ventilation improves the web moisture profile. Grott (88) discussed the fuel and power costs of pocket ventilation. Metcalfe (89) outlined the types of pocket ventilation equipment that are available. Gardner has written several papers (90,91,92) describing the principles involved in pocket ventilation and the moisture profile leveling advantages. Future ventilation research should quantify the interaction among the web, dryer fabrics, and ventilation system. Improved ventilation systems should do much to improve productivity and moisture profile uniformity.

DRYER FABRICS

The two main innovations in dryer fabrics have been the change from felts to open weave fabrics and the development of single felting. The open weave fabrics were discussed in some of the pocket ventilation articles (81-85).

Single felting is the term used to describe the use of serpentine dryer fabric in the first section to reduce web flutter. Sahay (92) and Josef (94) described applications of single felting to reduce flutter problems. Palazzolo (95) discussed the advantages and problems with single felting. Bringman and Jamil (96) compared single felting and impingement drying as solutions to the web flutter problem. Schlipf (97) measured the air temperatures and humidities in a single felting application. Wheeldon and Ashworth (98) measured the cylinder and sheet temperatures in single felting and conventional applications.

STEAM AND CONDENSATE SYSTEMS

The proper design and operation of steam and condensate systems are important in conventional and Yankee dryers. Much experimental and analytical work has been done on these systems. Simmons (99) gave an overview of dryer condensate removal and steam pressure control. Daane (100) presented the results of experimental work relating pressure differential, condensate flow rate, blow-through steam flow rate, dryer speed, and steam pressure from stationary and rotating siphons. Wahlstrom and Larsson (101) investigated the general characteristics of rotating and stationary siphons when in series with condensate piping. Gardner (102) calculated the minimum pressure differentials required for a rotary siphon. Appel and Hong (103) derived equations for the distribution of condensate rimming in a dryer and verified the results with experiments on a five-foot model. Calkins (104) has shown the effect of siphon clearance and dryer heat transfer. Hurm

(105-107) has written several articles on the principles of operation of dryer drainage systems. Hart (108) discussed steam and condensate system design considerations to reduce maintenance problems.

DRYER MEASUREMENTS AND EVALUATION

Most of the articles on dryer surveys have either focused on the instrumentation used or the survey results. Allan, et al. (109-111) discussed the instrumentation they developed and adapted for paper machine surveys. The instrumentation was used to measure moisture, basis weight, steam flow, condensate flow, air flow, dryer surface and sheet temperatures, and pocket wet and dry bulb temperatures. Luce, et al. discussed the use of infrared thermography (112) and video tape systems (113) in analyzing the performance of paper machines. Bennett (114), Fraser-Clark (115) and Rhorer (116) discussed the use of microwave moisture meters in analyzing moisture profile problems.

Other authors have emphasized the results of dryer tests. Montgomery (117) presented the results of moisture and temperature profile measurements from 40 different drying tests. Hoecke (118) reported the correlation between drying rate and steam pressure for linerboard and corrugating medium. Urbas (119), Wiseman (120), and Kerr (121) reported on surveys of Canadian newsprint machines. Garvin and Pantaleo (122) presented the survey methods and results of several dryer section testing programs. Chalmers (123) and Mardon, et al. (124) discussed the methodology of dryer heat and energy balances. Mardon, et al. (125-127) described the results of paper machine surveys. Other authors (128-130) have investigated the factors that affect CD moisture profiles.

CONCLUSIONS

As can be seen from the above, work has been done on most aspects of paper drying. Convective drying (including through, impingement, and floater drying) is the area that is best understood. The transport phenomena are well documented, and much experimental work has been done to correlate the transport coefficients.

Also much analytical and theoretical work has been done on steam pressure regulation and condensate removal. However, little has been done on the dynamics and control of the steam/condensate system.

Very little analytical work has been done on dryer ventilation and the effects of dryer fabrics on drying. Most of the work has been empirical and fragmented. A thorough analytical and experimental program is needed to quantify the effect of ventilation and fabrics on drying in a conventional drum dryer.

The instrumentation is available for conducting an adequate dryer survey. Much has been published on paper machine surveys; however, no suitable dryer model has been developed for comparing the thermal performance of dryers.

Very little has been done in the area of fundamental heat and mass transfer in paper webs. A thorough understanding of the transport phenomena could lead to the development of new methods of drying and improvements in conventional dryers.

It is recommended that future dryer research at IPC focus on two areas:

1. The improvement of the design, operation and control of conventional drum dryer sections.
2. The development of innovative methods of drying by a study of the fundamentals of paper web transport phenomena.

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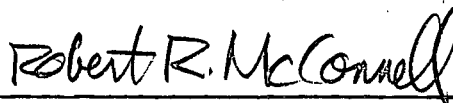
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